Available online at www.sciencedirect.com

SciVerse ScienceDirect

Polar Science 6 (2012) 183–195

http://ees.elsevier.com/polar/

Effect of radioactive pollution on the biodiversity of marine benthic ecosystems of the Russian Arctic shelf

Denis K. Alexeev*, Valentina V. Galtsova

Department of Applied Ecology, Russian State Hydrometeorological University, 98 Malookhtinsky Prospect, St. Petersburg, 195196, Russia

Received 1 August 2011; revised 2 March 2012; accepted 2 April 2012
Available online 24 April 2012

Abstract

This study is the result of many years of research on the ecology of the marine benthos of Russian Arctic seas. We used samples collected at various locations from the Russian continental shelf during 1993–2009 as the basis of our study. Our main aim was to analyze the spatial distribution of taxonomic and quantitative characteristics of the meiobenthos (small bottom-dwelling animals, 0.1–3.0 mm in size). Statistical analysis of the data revealed that the factors determining the spatial distribution of meiobenthic organisms under natural conditions, and conditions impacted upon by human activity, were salinity, water depth, hydrocarbons, heavy metals and radiocaesium volumetric activity. The possible use of the meiobenthos as a tool for environmental impact assessment is proposed and discussed on the level of higher taxa.

Keywords: Arctic seas; Meiobenthos; Marine ecology; Russian continental shelf; Environmental impact assessment

1. Introduction

In response to the ecological decline of recent years we must intensify our efforts to manage the environment to prevent further degradation. To achieve this, an understanding of biodiversity and, in particular, species composition is essential. The conservation of biodiversity is a typical problem for the Arctic seas, in which marine ecosystems were considered to be intact for many years but are now under increasing external pressure from economic activities in the ocean, as well as global environmental changes. Similar changes are also reflected in the structure of marine benthic ecosystems.

Conserving biodiversity consists of two parts: the acquisition of reliable species data and the formulation of adequate measures for their conservation. There are insufficient species data for marine ecosystems because large areas of the seafloor have yet to be analyzed at sufficient spatial and temporal resolution, and in such areas it is difficult to undertake repeated sampling. In addition to compiling taxonomical lists, it is also important to study benthic ecology.

The first species counts in Arctic seas were undertaken by Russian scientists in the middle of the 20th century; for example, Pergament (1944) found 1180 species in the Kara Sea, Ushakov (1952) reported 720 species for the Chukchi Sea, and Zenkevich (1963) reported species numbers for each sea except the East Siberian Sea. The richest of the Eurasian Arctic shelf seas is the Barents Sea, which is inhabited by

* Corresponding author.
E-mail address: dkalexeev@gmail.com (D.K. Alexeev).

1873-9652/$ - see front matter
doi:10.1016/j.polar.2012.04.001

3245 invertebrate species. The White Sea supports an impoverished Barents Sea fauna comprising 1817 species. The number of species steadily declines eastwards from the North Atlantic: 1671 species are known for the Kara Sea, 1472 for the Laptev Sea, 1011 species for the East Siberian Sea, and 1168 species for the Chukchi Sea (Buzhinskaja et al., 2001).

Marine benthic organisms can be divided into three groups by size: macro-, meio- and microbenthos. Generally, in marine ecology, the initial focus of attention when studying sea-bottom ecosystems is given to the macrobenthos. The macrobenthos comprises 60% of marine species, the meiobenthos 34%, and plankton 6%. Different benthic groups have been studied to varying degrees, with the study of species diversity starting with large organisms. The meiobenthos (small benthic organisms, 0.1–3.0 mm in size) and the microbenthos (<0.1 mm) are often excluded from marine research, which adds to the uncertainty inherent in investigations of both the biodiversity and functional ecology of sea-bottom ecosystems. Planktonic species are less diverse and more widely distributed compared with benthic animals, and our knowledge of them is more complete. The macrobenthos is, therefore, more frequently studied than the meiobenthos, and meiobenthic groups such as nematodes, turbellarians, harpacticoids, and ostracods are particularly poorly studied.

Meiobenthic organisms are an important part of marine ecosystems: their density can reach hundreds of thousands of individual organisms per square meter; the biomass is often comparable with the biomass of the macrobenthos, especially at greater depths. The meiobenthos feed on the large number of bacteria and bottom-dwelling unicellular algae, and thus consume a significant proportion of primary production, direct consumption of which is either unavailable or energetically unfavorable for many macrofauna. In turn, meiobenthic organisms serve as food for some invertebrates and fish. The meiobenthos play a significant role in the decomposition of organic matter and changes in the physical properties of sediments.

The composition of the meiobenthos includes various taxonomic groups of small multicellular organisms. Their systematic position is sometimes very poorly studied, and limited data are available relating to their ecology. Detailed study of dominant meiobenthic groups and species will enable us to get closer to understanding the ecology of small benthic invertebrates in various areas of the Arctic seas of Russia.

In recent years, interest in the study of the meiobenthos has increased dramatically. The research covers a wide range of subjects: morphology, systematics, the ecology of meiobenthic organisms, and molecular genetic studies. Biogeographic studies of the meiobenthos have also expanded the study of various geographic areas such as the abyssal zone, trenches, hydrothermal vents, as well as the polar regions of both hemispheres, and these are of particular interest. The volume of available information is already quite large, but its rate of accumulation is still high. For the meiobenthos there is a clear lack of review papers that analyze all stored data (such as the work of Higgins and Thiel, 1988; Galtsova, 1991; Giere, 2008; Mokievsky, 2009). Research on the meiobenthos of the Arctic continental shelf is extremely uneven. While the meiobenthos of the Barents, White, and Pechora seas, including the coast of Spitsbergen, has been studied in detail (e.g., Radziejewska and Stankowska-Radziun, 1979; Galtsova, 1991; Szymelfenig et al., 1995), few studies have examined the Eastern (Siberian) sector of the Arctic Ocean.

There have been quantitative studies of the meiobenthos in ecosystems of the Novosibirsk Shallows (Sheremetevskiy, 1987) from the intertidal zone to depths of 30 m; the Chauna Bay of the East Siberian Sea (Golikov et al., 1994); and estuarine areas of the Lena River (Gukov, 2001). Research of the Kara Sea benthos began long ago: it is thought to date back to A.E. Nordenskioeld's expeditions in 1875, 1876, and 1878 (Semenov, 1989). However, the meiofauna of the Kara Sea is now virtually unknown. There are a few taxonomic works that examine the diversity of nematodes in the Kara Sea (e.g., Galtsova and Kulangieva, 1999), and two works dedicated to the study of meiobenthic organisms collected from areas around the former nuclear test site Novaya Zemlya (Galtsova et al., 2004b; Pogrebov et al., 1997). The taxonomic composition and distribution of the meiobenthos in the Abrosimova and Stepovogo inlets, which are nuclear waste disposal sites, were both investigated in detail; samples were collected from depths ranging from 44 to 74 m.

There are two approaches to studying the ecology of marine meiobenthos. The first one concentrates on the ecology of major taxonomic rank (orders, classes). Such studies contribute to the overall picture of the significance of the meiobenthos and its separate component-groups within ecosystems, and aim to establish a common link between the characteristics of these groups and their relationship with the environment. The second one is associated with detailed study of the systematics of major groups and common species. It classifies small benthic organisms and provides keys to the identification of species.

In this study, we provide information on major meiobenthic taxonomic groups of the Russian continental shelf of Arctic seas. The aim is to analyze the spatial distribution of both taxonomic and quantitative characteristics of Russian Arctic meiobenthos communities.

2. Materials and methods

This study was based on material collected during expeditions carried out by the Zoological Institute of the Russian Academy of Sciences (Galtsova and Kulangieva, 1996) and by VNIIOkeangeologia (Pogrebov et al., 1997). Samples of meiobenthic organisms were collected aboard research vessels: the *Geologist Fersman* in August–September 1993, around Novaya Zemlya; the hydrographic ship *Captain Smirnitsky* in August–October 1995 on the international expedition "Seas and Estuaries of the Russian Arctic-95" (Galtsova et al., 2004a); and the research vessel *Nikolay Petrov* in September 2009 (Fig. 1). Collection and processing of samples were carried out according to the methods described in Galtsova and Kamenskaya (1993). Samples were collected from 113 locations at depths from 0.5 to 400 m. Samples were collected using a tubular corer, with three replicates from each sampling location. Material was extracted in the laboratory by washing the samples through a 63 μm mesh-size sieve and staining the samples with Rose Bengal solution. Specimens were identified to taxonomic rank based on Higgins and Thiel (1988). The mean weight of animals was calculated, based on the measurement of several dozen organisms of each group. The volume of animals was calculated as follows: the body of harpacticoids and animals with a spindle-shaped body was considered to have a half-cylinder circumscribing it; the volume of nearly cylindrical-shaped animals was considered equal to two-thirds of the cylinder volume. Thus, formulas obtained by Sheremetevskiy (1987) to calculate the average mass were used:

$$W_{1/2} = 0.39D^2Lr, \tag{1}$$

$$W_{2/3} = 0.52D^2Lr, \tag{2}$$

where D is the average maximum diameter, mm; L is the average length of the animal body, mm; and r is their weight, which for foraminifera, gastropods and bivalves was given as 1.5 mg/mm^3, and for other meiobenthos organisms was 1.13 mg/mm^3 (Wieser, 1960).

We used the Shannon–Weaver index H (Shannon and Weaver, 1963) to calculate taxonomic diversity and determine the degree of habitat saturation by each taxonomic group. The index was calculated as follows:

$$H = -K_i \sum_{i=1}^{n} \mathrm{Log}_2 K_i, \tag{3}$$

where $K_i = N_i/N$, N_i is taxon abundance, N is total abundance.

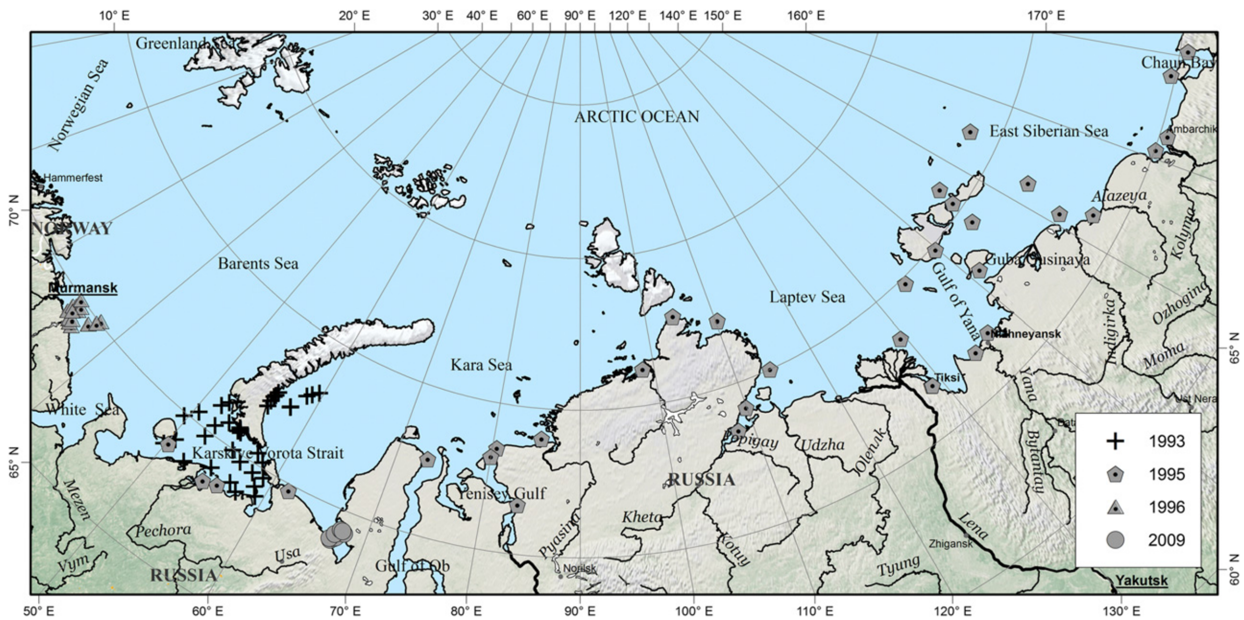

Fig. 1. Location of meiobenthos sampling sites and year of collection.

To assess the degree of contamination of marine sediments by radiocaesium, we used additional material collected by various expeditions: (1) an expedition organized by VNIIOkeangeologia where samples of soft-bottom sediments were collected aboard the RV *Geologist Fersman* in August–September 1993 around Novaya Zemlya (Pogrebov et al., 1997); (2) samples collected on cruises of the HS *Captain Smirnitsky* in August–October 1995 on the international expedition "Seas and Estuaries of the Russian Arctic-95" (Galtsova et al., 2004a); (3) an expedition of the RV *Akademik Boris Petrov* in the inner Kara Sea and the Ob Estuary (Stepanets et al., 2003); (4) data collected during the 1994 expedition to the estuarine section of the Yenisei River and Baidaratskaya Bay (Kuznetsov et al., 1994); and (5) several expeditions carried out using the Murmansk Marine Biological Institute's (MMBI) RV *Dalnie Zelentsy*. In 1993 the estuarine sections of the Ob and Yenisei rivers were examined (Rissanen et al., 1995) and the last three MMBI expeditions (2007–2009) covered parts of the Barents Sea, which included the standard section (Kola Section) in the central Barents Sea and the Franz Josef Land area. The focus of research in 2007–2008 was the eastern Barents Sea, when sections along the northeastern border, the area near the Novaya Zemlya western coast, and the section along the trenches in the southeast of the Barents Sea were investigated (Fig. 2). In 2009, the focus was on the western Barents Sea, when investigations along standard sections and in the Svalbard/Spitsbergen area were carried out (Leppänen et al., 2010).

3. Results

The meiobenthos comprises benthic organisms that are within the size range 0.1–3.0 mm for their entire life cycle, and also immature individuals of the macrobenthos. The meiobenthos is therefore divided into permanent (eumeiobenthos) and temporary (pseudomeiobenthos) components. The meiobenthos of the Russian continental shelf of the Arctic seas includes the following groups: the eumeiobenthos comprising *Foraminifera*, *Cnidaria*, *Turbellaria*, *Gnathostomulida*, *Nematoda*, *Kinorhyncha*, *Gastrotricha*, *Loricifera*, *Tardigrada*, *Harpacticoida*, *Ostracoda*, and *Halacarida*; and the pseudomeiobenthos comprising *Nemertini*, *Oligochaeta*, *Polychaeta*, *Tanaidacea*, *Cumacea*, *Amphipoda*, *Gastropoda*, *Bivalvia*, and *Asteroidea*. The taxonomic composition of the meiobenthos varied throughout the study area and locally between sampling locations. However, a few taxa formed a core group around which the taxon assemblages were based. *Foraminifera* and *Nematoda* were constant, while *Gastrotricha*, *Loricifera*, *Halacarida* and *Gastropoda* were rarely found. *Gastrotricha* was recorded in samples from the Khatanga Gulf, *Loricifera* from near the Anjou Islands, *Halacarida* from locations near the

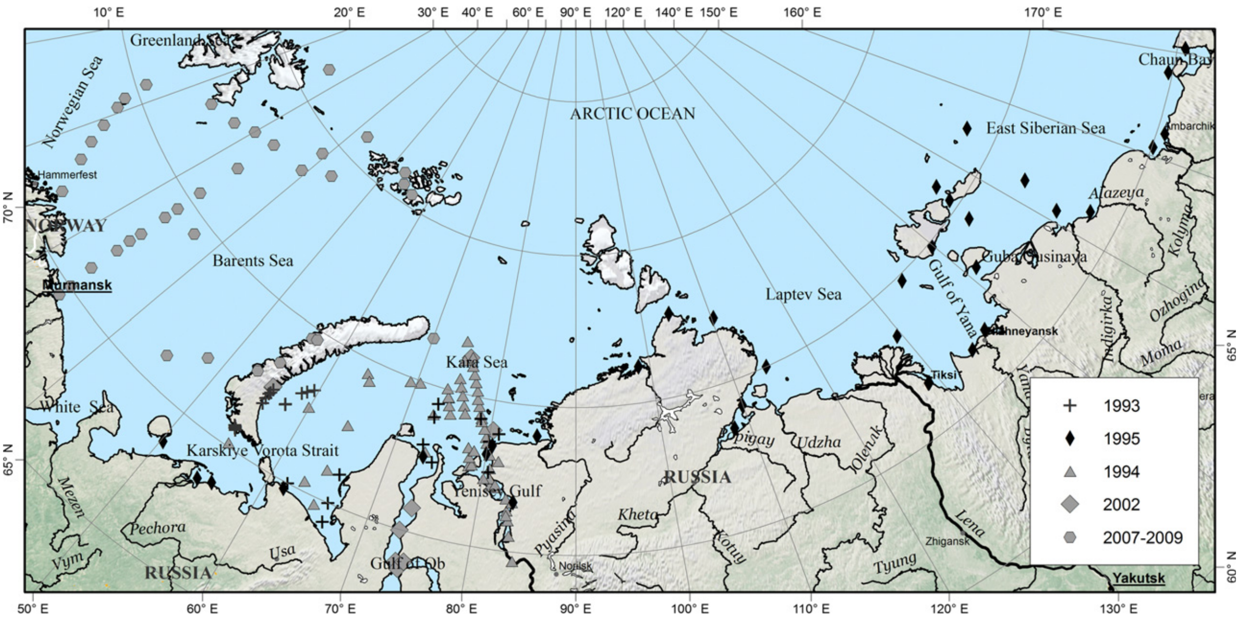

Fig. 2. Location of sampling sites where bottom sediment was collected, with the year of collection (1993–2009).

Pevek Port, and *Gastropoda* from the Vilkitsky Strait. *Cumacea* was found in sampling locations near the mouth of the Yana River in the Khatanga Gulf, and *Asteroidea* were recorded from Kolguev Island and the Khatanga Gulf. *Harpacticoida* were widely distributed throughout the study area but were not found at sampling locations near the Tiksi Port and the mouth of the Yana River. *Polychaeta* was absent from only four sampling locations: near the mouth of the Kolyma and Indigirka Rivers, between New Siberia and Kotelny islands, and in the Khatanga Gulf. The most diverse assemblage of taxa was recorded for sampling locations near Kolguev Island and the Anjou Islands, where 12 taxa were found. The lowest diversity of taxa was recorded around Tiksi Port, where only *Foraminifera*, *Nematoda*, and *Polychaeta* were found.

The Shannon–Weaver diversity index scores ranged from 1.21 to 2.61. The lowest index scores were generally associated with estuaries and ports (Fig. 3), probably due to the influence of freshwater from river run-off, but also as a result of anthropogenic impacts.

In addition to studying the qualitative composition of the meiobenthos, it is also of great interest to study its quantitative characteristics. Data on the abundance and biomass of the meiobenthic organisms sampled are presented in Table 1. Meiobenthos abundance, measured in thousands of individuals/m^2, varied from 10 to 2050. The lowest values were recorded from samples from the Tiksi Port, and the highest from localities near Kotelny Island (Fig. 4).

Meiobenthos biomass ranged from 255.1 to 47,327.9 mg/m^2. The lowest values for this measure were also found near Tiksi Port, while the maximum observed was for localities near Kolguev Island (Fig. 5).

The meiobenthos studied in the Murmansk Shallows, at depths ranging from 25 to 205 m, consisted of the following eumeiobenthos taxa: *Turbellaria*, *Nematoda*, *Ostracoda*, and *Harpacticoida*. Pseudomeiobenthos present included *Nemertini*, *Polychaeta*, *Oligochaeta*, *Bivalvia*, *Gastropoda*, *Isopoda*, *Tanaidacea*, and *Amphipoda*.

The Shannon–Weaver index scores for the Murmansk area (0.51–1.00) showed peaks and troughs in species diversity. Meiobenthos abundance ranged from 10,000 to 708,000 ind/m^2, and biomass from 1.18 mg/m^2 to 12.1 g/m^2. Meiobenthos abundance in samples from the Murmansk banks was within the range of 25,000–50,000 ind/m^2. The meiobenthic community was more abundant to the east, while western areas were more variable, with samples of both high and low abundance.

Samples from the Novaya Zemlya archipelago included the eumeiobenthos taxa: *Foraminifera*, *Cnidaria*, *Turbellaria*, *Gnathostomulida*, *Nematoda*, *Gastrotricha*, *Priapulida*, *Sipunculida*, *Ostracoda*, *Harpacticoida*, *Bryozoa*, and *Entoprocta*. This was a first record for both *Gnathostomulida*, and the small benthic metazoan *Entoprocta*, in the Barents Sea. The pseudomeiobenthos recorded comprised *Nemertini*, *Polychaeta*, *Oligochaeta*, and *Bivalia*. Eumeiobenthic

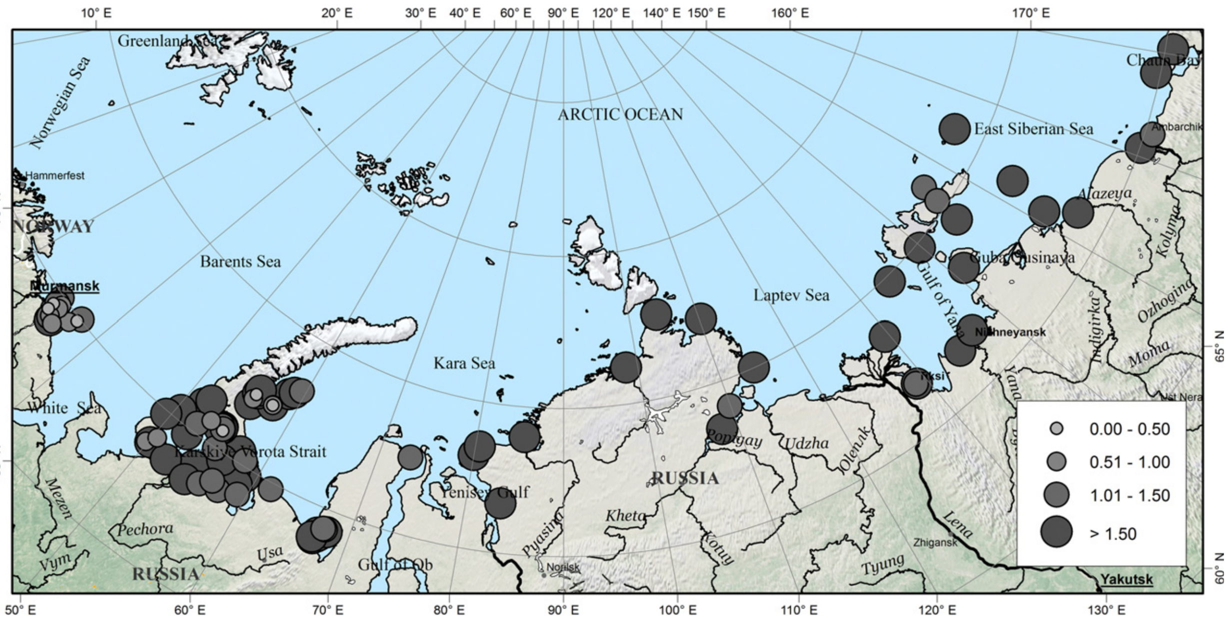

Fig. 3. Spatial distribution of meiobenthos biodiversity (Shannon–Weaver index).

Table 1
Meiobenthos abundance and biomass in 34 samples from the Russian continental shelf area of the Arctic seas. *N*, abundance (×1000 individuals/m^2); *B*, biomass (mg/m^2).

Taxon	Number of samples	*N*			*B*		
		Min	Mean	Max	Min	Mean	Max
Foraminifera	34	2	43	235	31	662	3657
Cnidaria	15	5	43	295	29	250	1723
Turbellaria	8	2	8	15	31	124	234
Gnathostomulida	10	3	12	35	10	46	133
Nematoda	34	4	307	860	7	497	1393
Kinorhyncha	17	1	15	40	3	49	133
Gastrotricha	1	3	3	3	540	540	540
Loricifera	1	3	3	3	27	27	27
Tardigrada	6	5	8	13	11	17	28
Harpacticoida	32	3	146	970	14	813	5393
Ostracoda	27	1	38	360	18	682	6455
Halacarida	1	3	3	3	31	31	31
Eumeiobenthos	34	9	550	1955	84	2663	9467
Nemertini	6	3	8	23	42	129	376
Oligochaeta	15	5	20	93	142	572	2623
Polychaeta	30	1	46	205	171	7784	35,006
Tanaidacea	8	1	7	10	55	369	546
Cumacea	3	3	4	5	1913	3189	3827
Amphipoda	7	3	5	10	1219	2265	4878
Gastropoda	1	3	3	3	316	316	316
Bivalvia	23	3	16	75	1146	7424	34,378
Asteroidea	2	5	5	5	3443	3443	3443
Pseudomeiobenthos	34	1	65	208	171	13,211	41,208
Meiobenthos	**34**	**10**	**615**	**2050**	**255**	**15,874**	**47,328**

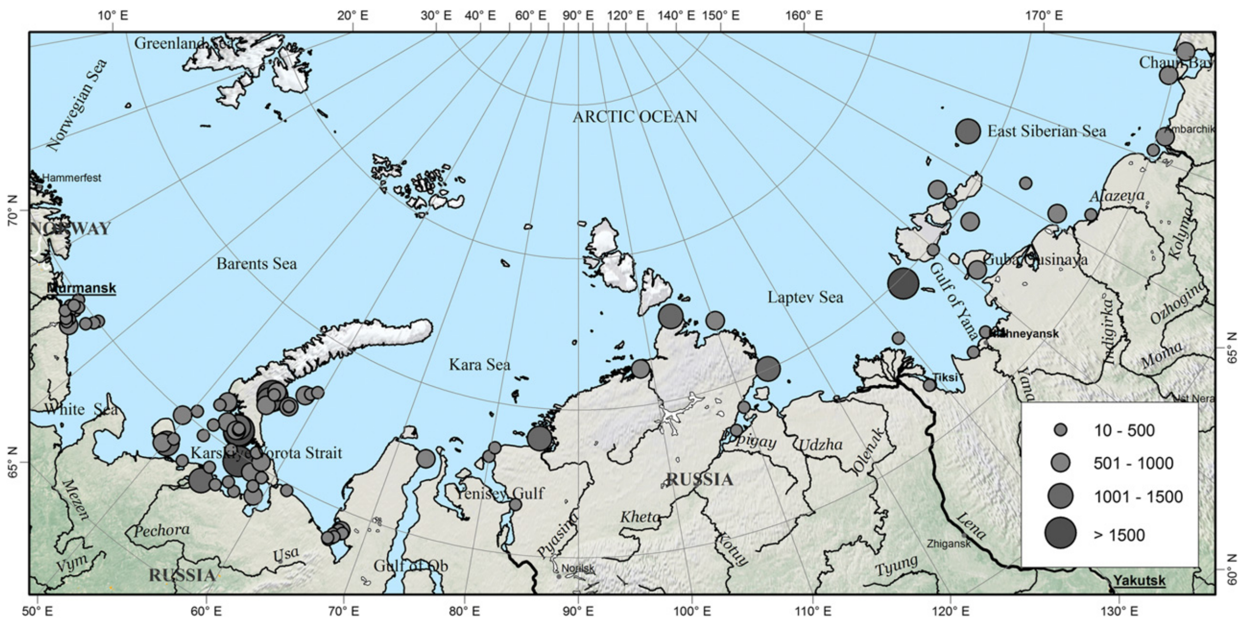

Fig. 4. Spatial distribution of meiobenthos abundance (×1000 ind/m^2).

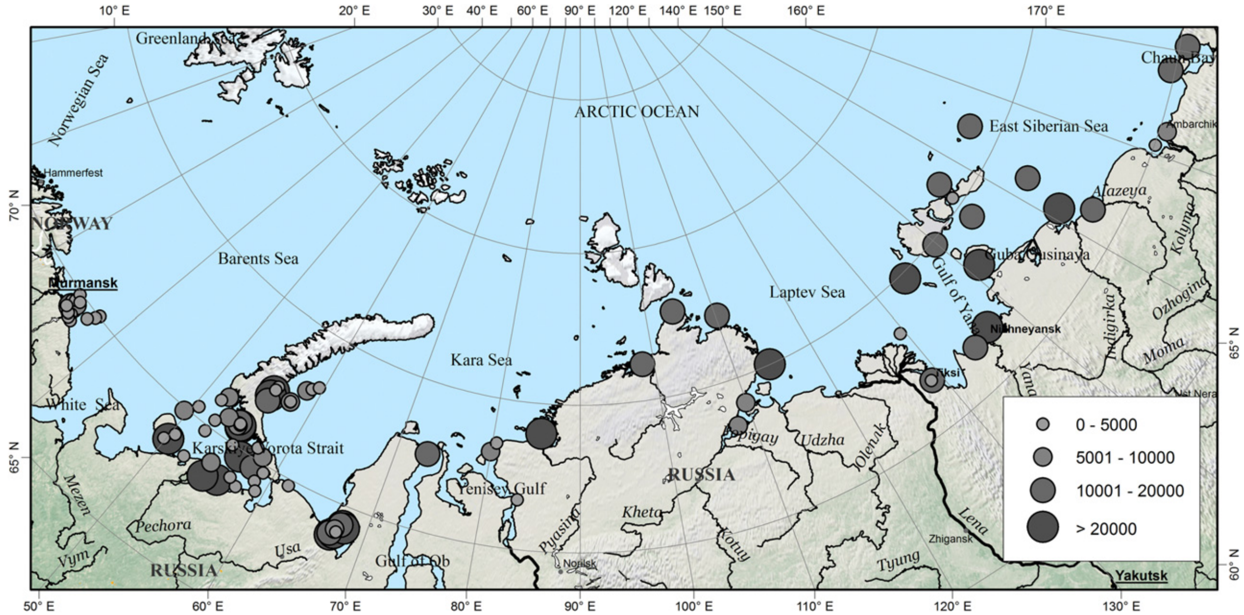

Fig. 5. Spatial distribution of meiobenthos biomass (mg/m^2).

organisms were dominant in both abundance and biomass at all sampling locations except two. Meiobenthos abundance for the Novaya Zemlya area varied from 108,000 to 5,426,000 ind/m^2, and biomass from 1.6 to 112 g/m^2. Quantitatively, foraminifera contribute 77% to the total abundance and up to 89% to the total biomass. Meiobenthic abundance was lowest in the central area of the bay, on clay and silty substrata. Meiobenthic communities were found to be richer in the open sea when compared with samples from the Chernaya Inlet. The abundance of meiobenthic organisms in the control stations collected in open waters away from Chernaya Inlet varied from 372,000 to 991,000 (mean, 580,000) ind/m^2. Biomass ranged from 4.9 to 19.6 g/m^2. Eumeiobenthos contribute 87% to the total population in terms of abundance, and up to 57% of the total biomass; this was also true for the Chernaya Inlet. In the open sea, free-living marine nematodes are the dominant group, and are responsible for 50% of the total abundance of the meiobenthos, whereas Polychaete larvae dominated the biomass.

4. Discussion

The analysis of benthic communities is an informative and useful tool for monitoring the state of marine ecosystems. Relative to other groups of organisms, the benthos is highly stable in space and time, and therefore can be used as a predictive tool in determining changes in the marine ecosystem.

In monitoring studies, there are advantages to focusing on the meiofauna rather than the macrofauna (Ott and Galtsova, 2002). Meiobenthic animals are highly abundant but also sensitive to pollution. Statistical analysis of meiobenthic data therefore enables us to draw conclusions on the effect of pollution on species composition. Meiobenthic animals lack a planktonic phase and thus are more consistently exposed to accumulations of pollutants locally. The short generation-cycles and rapid growth of the meiofauna result in a much faster response to pollutants such as heavy metals and radioactive contamination, compared with the macrofauna. However, the meiobenthos is relatively insensitive to mechanical disturbance and destabilization of the sediment. Within the meiobenthic groups, some taxa, such as harpacticoid and ostracod crustaceans, are highly sensitive and extremely useful indicators of pollution.

When using living organisms as indicators of ecological change in ecosystems, it is important to identify which are the primary ecological factors that influence spatial distribution both in natural (undisturbed) habitats and in areas influenced by anthropogenic activity. In a previous study, it was established that under natural conditions the limiting factors are the granulometric composition and the organic content of the sediment (Galtsova and Kulangieva, 1996). One of the objectives of this study was therefore to establish which factors determine the distribution of the meiobenthos in areas affected by anthropogenic impacts.

Using stepwise multiple linear regression (log-transformed) (Hastie et al., 2009) we found relationships between the main environmental parameters measured during the "Seas and Estuaries of the Russian Arctic-95" expedition and the distribution of meiofauna:

$$\text{Foraminifera}\ (n=34, \text{Multiple-}R=0.567, \sigma=1.16, F=4.74, F_{\text{st}}=2.28)\\ \ln(N_1)=5.2+0.67\ln(S+1)-0.91\ln(^{226}\text{Ra})-0.54\ln(\text{Co}+1), \tag{4}$$

$$\textit{Gnathostomulida}\ (n=10, \textit{Multiple-R}=0.679, \sigma=0.6, F=6.85, F_{st}=3.59)\\ \ln(N_2)=-0.87+0.99\ln(^{226}Ra+1), \tag{5}$$

$$\textit{Nematoda}\ (n=34, \textit{Multiple-R}=0.824, \sigma=0.75, F=13, F_{st}=2.16)\\ \ln(N_3)=-23.9+11.1\ln(pH)+0.92\ln(Slt)+0.43\ln(H)+0.59\ln(S+1)-0.35\ln(OM), \tag{6}$$

$$\textit{Kinorhyncha}\ (n=17, \textit{Multiple-R}=0.625, \sigma=0.93, F=9.01, F_{st}=3.10)\\ \ln(N_4)=1.0+0.59\ln(^{137}Cs+1), \tag{7}$$

$$\textit{Harpacticoida}\ (n=32, \textit{Multiple-R}=0.543, \sigma=1.21, F=8.03, F_{st}=2.89)\\ \ln(N_5)=8.6+0.46\ln(^{137}Cs+1)-1.3\ln(Cu), \tag{8}$$

$$\textit{Ostracoda}\ (n=27, \textit{Multiple-R}=0.742, \sigma=0.87, F=9.37, F_{st}=2.35)\\ \ln(N_6)=-14.3+3.94\ln(^{40}K)-2.0\ln(S+1)-0.34\ln(D+1), \tag{9}$$

$$\textit{Oligochaeta}\ (n=15, \textit{Multiple-R}=0.709,\ \sigma=0.72, F=6.05, F_{st}=2.86)\\ \ln(N_7)=5.9+0.45\ln(Asph)+0.28\ln(C_{car}), \tag{10}$$

$$\textit{Polychaeta}\ (n=30, \textit{Multiple-R}=0.790, \sigma=0.79, F=7.95, F_{st}=2.11)\\ \ln(N_8)=6.8+1.7\ln(Slt)-1.2\ln(Ni)-0.75\ln(Co)-1.0\ln(OM)+0.60\ln(Asph), \tag{11}$$

$$\textit{Bivalvia}\ (n=23, \textit{Multiple-R}=0.524, \sigma=0.8, F=7.94, F_{st}=2.97)\\ \ln(N_9)=-5.7+1.9\ln(O_2), \tag{12}$$

$$\textit{Meiobenthos}\ (n=34, \textit{Multiple-R}=0.907, \sigma=0.48, F=21, F_{st}=2.01)\\ \ln(N_9)=-24.2+11.1\ln(pH)+0.82\ln(Slt)+0.37\ln(S+1)-0.49\ln(OM)+0.16\ln(^{137}Cs+1)+0.73\ln(O_2), \tag{13}$$

where N is meiobenthos abundance, in thousands of individuals/m^2; S is salinity, ‰; ^{226}Ra is radioradium content, Bq/kg; Co is cobalt content, ppm; pH is pH-value; Slt is the content of clay minerals, %; H is depth, m; OM is organic matter content of sediments, %; ^{137}Cs is radiocaesium content, Bq/kg; Cu is copper content, ppm; ^{40}K is radiopotassium content, Bq/kg; D is water clarity, %; Asph is asphaltenes content, %; C_{car} is the content of carbonate carbon, %; Ni is nickel content, ppm; O_2 is oxygen content, %; n is the number of cases; Multiple-R is the multiple coefficient correlation; F is Fisher's exact test; and σ is the standard error of the estimate.

A general overview of the available data indicates high variability in the environmental conditions that characterize the marine ecosystems of the study area, including many environmental variables that are important for the health of the benthos, including temperature, salinity, and water transparency. Measurements of the water temperature in the benthic zone at sample locations varied by up to 12 °C, salinity varied by 35‰, and water transparency by 90% of the maximum value. Sediments were also diverse, from fine-grained pelite near the mouth of the Indigirka River, to sand–gravel–pebble sediment in Khatanga Bay. The pH-value showed the least variation, and was never more than 8.0, and rarely lower than 7.0. pH-value below (to 6.95) or equal to neutral were recorded at sampling locations in Dickson and Tiksi ports, and the Gulf of Buor-Hai. In these locations, oxygen deficiency was greatest (to a maximum of 0.46 mg/dm^3 in the Gulf of Buor-Hai, and 3.68 mg/dm^3 in Port Dickson). Higher nitrate concentrations relative to background levels (more than 1 mg/dm^3) were observed throughout the Pechora and Ob inlets, Tiksi

Bay, and the mouth of the Indigirka River, although higher concentrations were occasionally recorded some distance from the coast, probably indicating inflow from deep water. Nitrite levels in excess of average levels (more than 0.7 mg/dm^3) were observed in the Lena and Indigirka estuaries.

Relatively high concentrations of ammonium ions (20 mg/dm^3) were recorded in the water in the Taimyr and Pyasina estuaries, and in the Yenisei Gulf. Significant contamination of the sediment by hydrocarbons, with recorded concentrations 14 times higher than the expected average, or 120 times the expected minimum was shown near Tiksi Port.

Given that marine sediments are a major habitat for meiobenthic organisms, the physical and chemical properties of the sedimentary environment is of great importance. The particle size, shape, and degree of packing determine the volume of interstitial space in the sediment, and therefore, the pore water content and the flow of water through the sediments. Pore water is saline, contains dissolved oxygen, and also contains dissolved organic matter, which is a food source for some meiobenthic groups. One of the aims of our study was to identify the properties of sediment that affect the distribution of meiobenthic organisms; i.e., the clay fraction content. In their earlier research, Gurevich and Hasankaev (1976) demonstrated that the content of silt–pelites in the sediment is one of the most important parameters determining the physicochemical and geochemical properties, and therefore, the ecological conditions of potential habitats. For example, the quantitative distribution of many meiobenthic groups (nematodes, oligochaetes, polychaetes, and juvenile bivalve mollusks) showed a strong correlation with the percentage of silt and pelite.

Another important parameter is depth: the response to changes in temperature, light, the sedimentary environment, and food distribution at different depths may be apparent from changes in population size or diversity. In our analysis, using cumulative curves plotting depth against taxa biodiversity and density, we were able to detect the effect of depth on nematodes. We identified multiple homogeneous regions at depths of 0–10 m, 10–70 m, and >70 m (Fig. 6).

Numerous studies have shown that the absence of oxygen, which can lead to the presence of hydrogen sulphide, is an important factor in determining the distribution of benthic organisms. Oxygen content has an effect on the population density of *Bivalvia* and other meiofauna.

Galtsova (1976) studied the effect of salinity on the population dynamics of nematodes. In particular, she found that many species of free-living nematodes are euryhaline. In this study, we found salinity also to be a determining factor for *Ostracoda*, with increased salinity correlating with a decrease in the number of animals. In addition to salinity, water clarity is also an important parameter determining the population size and its distribution. The clarity of the water has a strong influence on available light, which is a determining factor in the vertical distribution of the microphytobenthos, a major source of food for many groups of meiobenthos (Galtsova, 1991).

A further parameter determining the Arctic distribution of meiobenthic organisms is pH. We found a relationship between pH and the meiobenthos

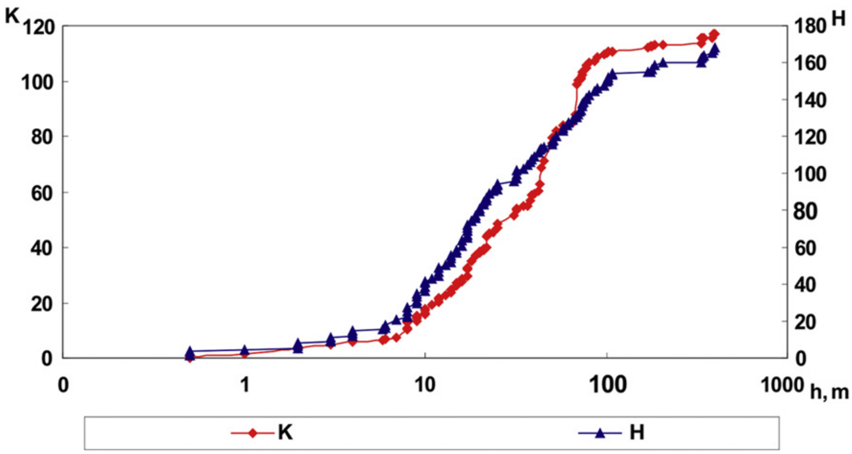

Fig. 6. Cumulative curves of changes in meiobenthos abundance and biodiversity with depth. h, depth (m); H, diversity (Shannon–Weaver Index); K, mean abundance for sample sites "i" ($K_i = N_i/\overline{N}$, where N_i is taxon abundance, N is total abundance).

distribution, in particular *Nematoda*. Seawater typically has a pH of 8.1–8.4. Higher levels of acidity (pH $<$ 7) than the background level of the seawater are found where there is a high percentage of clay and silt fractions in sediments that are also rich in organic matter. While sediments with high organic matter content may offer a suitable habitat for meiobenthic animals, oxygen-poor conditions can prevent colonization (Pavlova, 1976).

We investigated the effect of the following factors on the meiobenthos: the clay content of the sediment, water depth, oxygen concentration, salinity, transparency, pH, and organic matter content. We also considered the relationship between the distribution of meiobenthic organisms and the content in the sediment of: carbonate carbon (Ccar) and asphaltenes (Asph); heavy metals (Co, Cu, Ni, V); and the radioactive isotopes ^{137}Cs, ^{40}K, and ^{226}Ra. An increase in heavy metal concentrations always leads to a decrease in the population density of meiobenthic organisms (these elements are typical toxicants). The influence of radioactive isotopes is not so straightforward.

Radioactive pollution of marine ecosystems is one of the most dangerous anthropogenic impacts on the biota. Radioactive pollution results from the discharge of contaminated water from industry, the disposal of radioactive waste, and accidental contamination following mechanical failure on atomic submarines. Several areas in the Russian Arctic seas have been exposed to significant contamination by radionuclides.

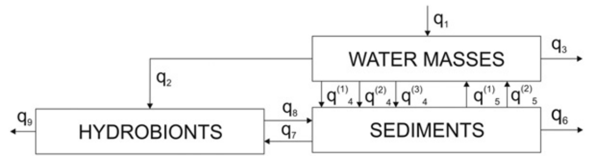

Fig. 8. Schematic diagram of migration paths of radionuclides in aquatic ecosystems. q_1 – input from external sources of radioactive contaminants; q_3, q_6, q_9 – irreversible loss of contaminant from the water, biota, and bottom sediments; q_2 – consumption of contaminant from the water by hydrobionts; q_8 – pollutants in bottom sediments due to the secretions of aquatic organisms and their post-mortem decay; q_7 – consumption of pollutants in the sediments by hydrobionts; $q_4^{(1)}$ – intake of radioactive contaminants from a water reservoir in the seafloor due to the deposition of mineral sediment and filtration; $q_4^{(2)}$ – intake of radioactive contaminants due to the sorption of dissolved contaminants in sediments; $q_5^{(1)}$ – release of radioactive contaminants from the sediments back into the water; $q_4^{(3)}$ – deposition of suspended sediment in the water into the sediment; $q_5^{(2)}$ – the previous process in reverse.

Chernaya Bay is the location of one of the former underwater, atmospheric, and underground Novaya Zemlya nuclear test sites; the Abrosimova and Stepovogo inlets on the east coast of the Novaya Zemlya archipelago have been used for underwater storage of barges, ships and containers containing radioactive waste. The Obskaya Inlet and the Yenisei Gulf were exposed to radionuclides from contaminated inflow via rivers for many years. The spatial distribution of radiocaesium in marine sediments of the Arctic seas of Russia is presented in Fig. 7.

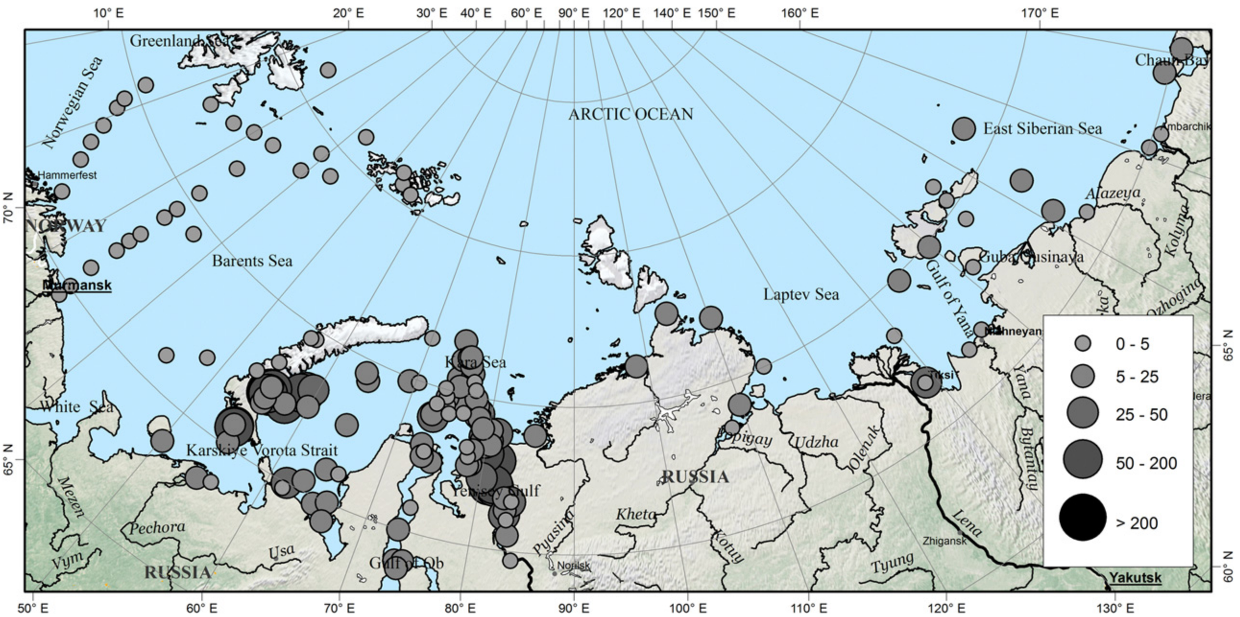

Fig. 7. Radiocaesium volumetric activity (Bq/kg) in bottom sediments in various areas of Russian Arctic Seas.

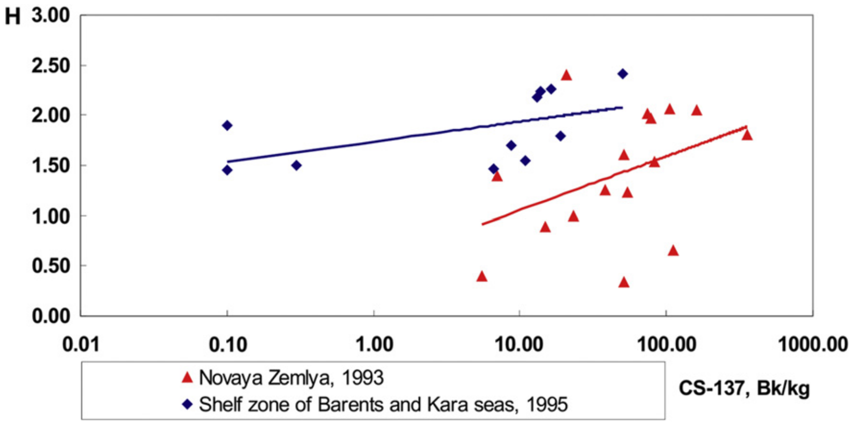

Fig. 9. Relationship between taxonomic diversity of meiobenthos and radiocaesium volumetric activity in samples located in the Barents and Kara seas (Galtsova and Alexeev, 2009), showing a positive correlation. *H*, diversity (Shannon–Weaver index).

In sandy and gravel–pebble sediments of offshore areas, radiocaesium has accumulated in low quantities (1–8 Bq/kg). To the east of Novaya Zemlya on the continental shelf, the concentration of radiocaesium in the sand and coarse-grained sediments varies from 3 to 10 Bq/kg, although the value is much higher in some depressions in the bays; e.g., the Stepovoy Gulf, where muddy bottom sediments contain high concentrations of ^{137}Cs, up to 90 Bq/kg. The concentration of ^{137}Cs is 0.8–6.2 Bq/kg in sediments of Baidaratskaya Bay and in shallow waters near Sharapov Cats. This is typical for these types of coastal marine sediments. The bottom sediments at depths of 95 m to the north of the Ugra Peninsula, where silty sediment radiocaesium content is up to 27–31 Bq/kg, appear anomalous. In the sandy sediments of the shallow waters between the Yamal Peninsula and the Severnaya Zemlya archipelago, ^{137}Cs concentration varies from 4 to 10 Bq/kg; in this zone the level of radiocaesium increases to 15–18 Bq/kg in silt-filled hollows. The highest concentrations recorded are in the clayey mud channels associated with Siberian rivers. Along the Ob-Yenisey coast, large volumes of suspended contaminants in river water drain into the Kara Sea.

Fig. 8 shows a schematic diagram of the migration of radionuclides in aquatic ecosystems. The biotic components of aquatic ecosystems play an essential role in the redistribution of pollutants, including radionuclides. We can conclude, from available research (Ilus et al., 1993; Kuznetsov et al., 1995), that macrobenthic communities are the most inert component of marine bottom ecosystems. Many of the major macrobenthic organisms can live for several years. Therefore, this category of benthos is slow to respond to an increase in radioactivity levels in their environment, which would be reflected either by a change in

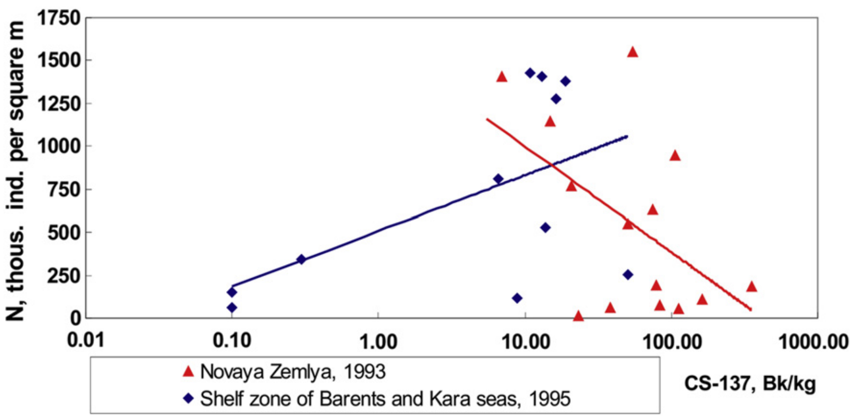

Fig. 10. Relationship between meiobenthos abundance and radiocaesium volumetric activity in samples collected in the Barents and Kara seas (Galtsova and Alexeev, 2009).

population structure or species diversity. A substantial build-up of radionuclide concentration in the macrobenthos is therefore highly probable and to be expected, especially in mobile and fixed sestonophages, detritophages, and deposit-feeders.

There are few studies focusing on the influence of radioactive pollution on meiofauna. Galtsova and Alexeev (2009) analyzed the relationship between the biodiversity and abundance of meiobenthic organisms and radiocaesium volumetric activity using material collected from: around the Novaya Zemlya nuclear test site in the Chernaya Bay (depth 31–87 m) during an expedition on the RV *Geologist Fersman*; the Stepovogo and Abrosimova inlets (44–74 m); around the Novozemelskaya Depression (333–403 m); and the shelf zone of the Barents and Kara seas, including the Ob Inlet and Yenisei Gulf aboard the hydrographic ship *Captain Smirnitsky* in 1995. There is a positive correlation between radiocaesium concentration and the taxonomic diversity of meiobenthos (Fig. 9). However, the effect of cesium-137 concentration on the quantitative measure of meiobenthos abundance is ambiguous. It is likely that small concentrations of ^{137}Cs have no effect on, or can even lead to insignificant increases in, the abundance of the meiobenthos. At greater levels of contamination (*c.* 20 Bq/kg), however, there is a negative effect on meiobenthos abundance that may be irreversible, representing a tolerance threshold (Fig. 10). In conclusion, the meiobenthos reacts to radioactive pollution through changes in diversity and abundance faster than the macrobenthos, which is more stable and shows fewer effects in the short-term. However, in the long-term, the macrobenthos may show greater accumulation of radionuclides in their cells and tissues.

5. Conclusion

The following groups of eumeiobenthos were found in Russian Arctic seas: *Bryozoa*, *Cnidaria*, *Entoprocta*, *Foraminifera*, *Gastrotricha*, *Gnathostomulida*, *Halacarida*, *Harpacticoida*, *Kinorhyncha*, *Loricifera*, *Nematoda*, *Ostracoda*, *Priapulida*, *Sipunculida*, and *Tardigrada*. Pseudomeiobenthos included: *Amphipoda*, *Asteroidea*, *Bivalvia*, *Cumacea*, *Decapoda*, *Gastropoda*, *Gnathostomulida*, *Holothuroidea*, *Nemertini*, *Nudibranchia*, *Oligochaeta*, *Polychaeta*, *Polychaeta*, *Priapulida*, and *Tanaidacea*. The Shannon–Weaver diversity index scores varied from 0.00 to 2.61, with a mean of 1.44. Meiobenthos abundance and biomass varied considerably between sampling locations, by two to three orders of magnitude. The lowest abundance recorded was 1000 ind/m^2; the highest 5,426,000 ind/m^2. The highest biomass recorded was 118,870 mg/m^2, and the lowest 3 mg/m^2. Nematodes were usually the dominant group. Within the meiobenthos, the eumeiobenthos were usually the most abundant, while the pseudomeiobenthos had the greatest biomass.

In coastal waters and estuaries of the Russian Arctic that are affected by anthropogenic activity, the main factors determining the spatial distribution of benthic organisms are: (1) natural environmental variables of the water and sediment (i.e., salinity, transparency, pH, oxygen, and grain size); (2) the content of hydrocarbons in sediments (such as the content of asphaltenes, which is probably anthropogenic in origin); (3) heavy metal content of the sediment (Co, Ni, Va, Cu); and (4) radionuclide content of the sediment (^{226}Ra, ^{40}K, ^{137}Cs), which can be both natural and/or anthropogenic in origin.

Acknowledgments

This research project would not have been possible without the support of many people. The author wishes to express gratitude to rector of the Russian State Hydrometeorological University, Prof. Dr. L. Karlin, and to Faculty of Ecologies and Physics of Nature for providing the financial means and laboratory facilities. The author would also like to convey thanks to department head, Prof. Dr. V. Shelutko who was abundantly helpful and offered invaluable assistance, support and guidance. Deepest gratitude is also due to the members of the ISAR-2 organizing committee for the invitation and editors for their help in preparing articles for publication.

References

Buzhinskaja, G.N., Andriashev, A.P., Balushkin, A.V., Neyelov, A.V., Markhaseva, E.L., Stepanjants, S.D., Lukina, T.G., 2001. List of species of free-living invertebrates of Eurasian Arctic seas and adjacent deep waters. Explorations of the Fauna of the Seas 51 (59), Zoological Institute of Rus. Acad. Science, St. Petersburg, pp. 129 (in Russian).

Galtsova, V.V., 1976. Free-living marine nematodes as a component of the meiobenthos of Chupa Bay of the White Sea. Explorations of the Fauna of the Seas 15 (23), Nauka, Leningrad, pp. 165–170 (in Russian).

Galtsova, V.V., 1991. Meiobenthos in marine ecosystems (with special reference to freeliving nematodes). Proceedings of the Zoological Institute of the Russian Academy of Sciences 224. Leningrad (in Russian).

Galtsova, V., Alexeev, D., 2009. Benthic communities of Russian Arctic Seas under radioactive pollution condition. Radioprotection 44, 713–718.

Galtsova, V.V., Kamenskaya, O.E., 1993. Method of investigation of deep see meiobenthos. In: Kuznetsov, A.P., Sokolova, M.N. (Eds.),

Food of Marine Invertebrates in Different Vertical and Latitudinal Zones. Institute of Oceanology, Moscow, pp. 91–94 (in Russian).
Galtsova, V.V., Kulangieva, L.V., 1996. Meiobenthos of the Yarnishnay inlet of the Barents sea. Russian Journal of Marine Biology 22, 3–9 (in Russian).
Galtsova, V.V., Kulangieva, L.V., 1999. Biodiversity of nematodes of the Arctic seas of Russia. Proceedings of the Zoological Institute of the Russian Academy of Sciences 280, 52–53 (in Russian).
Galtsova, V.V., Kulangieva, L.V., Alexeev, D.K., 2004a. Assessment of the ecological condition of an area of the Arctic continental shelf under anthropogenic impact. In: Karlin, L., Shelutko, V., Frumin, G., Galtsova, V., Dmitriev, V., Gutnichenko, V. (Eds.), Ecological and Hydrometeorological Problems of Large Cities and Industrial Areas. RSHU, St. Petersburg, pp. 43–48 (in Russian).
Galtsova, V.V., Kulangieva, L.V., Pogrebov, V.B., 2004b. Meiobenthos of the former nuclear test area and nuclear waste disposal grounds around the Novaya Zemlya Archipelago (Barents and Kara Seas). Russian Journal of Marine Biology 30, 231–240 (in Russian).
Giere, O., 2008. Meiobenthology: The Microscopic Fauna in Aquatic Sediments. Springer-Verlag.
Golikov, A.N., Gagaev, S.Yu., Galtsova, V.V., Golikov, A.A., Dunton, K., Menshutkina, T.V., Novikov, O.K., Petrjashev, V.V., Potin, V.V., Sirenko, B.I., Schonberg, S., Vladimirov, M.V., 1994. Ecosystems and flora and fauna of the Chaun Bay of the East-Siberian Sea. Explorations of the Fauna of the Seas 55, Zoological Institute of Rus. Acad. Science., St. Petersburg, 129, pp. 4–111 (in Russian).
Gukov, A.U., 2001. Hydrobiology of the Mouth of the Lena River. Scientific World, Moscow (in Russian).
Gurevich, V.V., Hasankaev, V.B., 1976. Lithological parameters of littoral shallows biogeocenoses of Dalniy beach. In: Gurevich, V.I., Strelcov, V.E. (Eds.), Studies on the Ecology of the Sandy Littoral Zone. MMBI, Apatity, pp. 3–25 (in Russian).
Hastie, T., Tibshirani, R., Friedman, J., 2009. The Elements of Statistical Learning: Data Mining, Inference and Prediction. second ed., Springer Series in Statistics.
Higgins, R.P., Thiel, H., 1988. Introduction to the Study of Meiofauna. Smithsonian Institution Press, Washington, D.C.
Ilus, E., Sjoblom, K.-L., Ikaheimonen, T.K., 1993. Monitoring of radionuclides in the Baltic Sea in 1989–1990. STUK-A 105, 35.
Kuznetsov, A.P., Dando, P., Shmelev, I.P., Denisenko, S.G., Efimov, B.V., Demidov, A.M., Shunko, V.M., 1995. Radioactive nuclides in the bottom fauna around the wreck of the nuclear submarine "Leninsky Komsomol" in the Norwegian Sea. Izvestiya RAN. Biological Series 4, 467–471 (in Russian).
Kuznetsov, Yu. V., Rezenkov, Y.A., Legin, V.K., Rakov, N.A., Zhidkov, V.V., Savitsky, Yu. V., Tishkov, V.P., Pospelov, Yu. N., Egorov, Yu. M., 1994. An assessment of the contribution of the Yensei River to the overall radioactive contamination of the Kara Sea. Radiochemistry 36 (6), 546–552.
Leppänen, A.P., Kasatkina, N., Matishov, G., Solatie, D., 2010. Radioecological studies in the Barents Sea (results of expeditions in 2007–2009). In: Proceedings of Third European IRPA Congress 2010, June 14–18. http://www.irpa2010europe.com/pdfs/proceedings/S16-P16.pdf.
Mokievsky, V., 2009. Ecology of Marine Meiobenthos. KMK Scientific Press, Moscow (in Russian).
Ott, J., Galtsova, V.V., 2002. The ecology of marine meiobenthos: progress, trends and applied aspects. In: Proc. 3rd International Congress "Environmental Micropaleontology, Microbiology and Meiobenthology", Vienna, Austria, 2002, pp. 157–159.
Pavlova, L.G., 1976. Physico-chemical parameters and their dynamics in the sediments of intertidal flats. In: Gurevich, V.I., Strelcov, V.E. (Eds.), Studies on the Ecology of the Sandy Littoral Zone. MMBI, Apatity, pp. 30–39 (in Russian).
Pergament, T.S., 1944. Benthos of the Kara Sea. Problems of the Arctic and Antarctic 1, 102–132 (in Russian).
Pogrebov, V.B., Fokin, S.I., Galtsova, V.V., Ivanov, G.I., 1997. Benthic communities as influenced by nuclear testing and radioactive waste disposal off Novaya Zemlya in the Russian Arctic. Marine Pollution Bulletin 35, 333–339.
Radziejewska, T., Stankowska-Radziun, M., 1979. Intertidal meifauna of Recherchefjorden and Malbukta, Vest Spitsbergen. Sarsia 64, 253–258.
Rissanen, K., Matishov, D., Matishov, G., 1995. Radioactivity levels in Barents, Petshora, Kara, Laptev and White Sea. In: Strand, P., Cooke, A. (Eds.), Environmental Radioactivity in the Arctic. Proceedings of the Second International Conference on Environmental Radioactivity in the Arctic. Oslo, Norway, August 1995, pp. 208–214.
Stepanets, O.V., Borisov, A.P., Ligaev, A.N., Yu, Solovjeva G., Sisov, E.M., Komarevsky, V.M., 2003. Study of anthropogenic pollution in the Kara Sea and adjacent estuaries of Yenisei and Ob in 2002. In: Schoster, F., Levitan, M. (Eds.), Scientific Cruise Report of the joint Russian-German Kara Sea Expedition in 2002 with RV "Akademik Boris Petrov". Ber. Polarforsch. Meeresforsch 450, 72–84.
Semenov, V.N., 1989. Long-term changes of benthic biocenoses of Kara Sea and adjacent waters. In: Matishov, G.G. (Ed.), Ecology and Bioresources of Kara Sea. KSC AN SSSR Academy of Sciences, Apatity, pp. 145–150 (in Russian).
Shannon, C.E., Weaver, W., 1963. The Mathematical Theory of Communication. University of Illinois Press, Urbana, IL.
Sheremetevskiy, A.M., 1987. The role of meiobenthos in ecosystems of the southern shelf of Sakhalin, East Kamchatka and Novosibirsk shallows. Research Fauna of the Seas 35 (43). Nauka, Leningrad (in Russian).
Szymelfenig, M., Kwasniewski, S., Weslawski, J.M., 1995. Intertidal zone of Svalbard 2. Meiobenthos density and occurrence. Polar Biology 15, 137–141.
Ushakov, P.V., 1952. Chukchi Sea and its bottom fauna. In: Ushakov, P.V. (Ed.), The Far North-East of the USSR. The Fauna and Flora of the Chukchi Sea, vol. 2. Academy of Sciences of USSR, Moscow, pp. 5–82 (in Russian).
Wieser, W., 1960. Populationsdichte und Vertikalverbreitung der Meiofauna mariner Boden. Int. Rev. Ges. Hydrobiol. 45, 487–492 (in German).
Zenkevich, L.A., 1963. Biology of the Seas of USSR. Academy of Sciences of USSR, Moscow (in Russian).